General Physics Lab 7

Inverse-Square Law of Light

Objectives:

- To observe the inverse-square law relationship between the intensity of light and the distance from the source

Equipment:

- Multimeter with Probes
- Breadboard
- Jumper Wire Kit
- 2 Alligator Clip Wires
- 9V Battery
- 9V Battery Connector
- 470 Ω Resistor
- 1 kΩ Potentiometer
- 2 White LEDs
- Modelling Clay
- Ruler
- Protractor (or other straight edge)
- Tape

Physical Principles:

Intensity of Light

A light source appears fainter when it is farther away. In Fig. 1, you can see that distant light sources appear fainter than nearby sources. It helps to define a few of the quantities associated with light and sources.

Fig. 1: Inverse-square law of light intensity – the street light intensity decreases with distance

Power, P_S, (in units of Watts) is defined to be the total amount of light energy radiated by a source every second.

$$P_S = \frac{Energy}{t} \tag{1}$$

Intensity, I, is a measure of the brightness of light at some location far from the source. The intensity of light, I, at some location is defined as the power of radiation passing through a unit area at that point. Thus,

$$I = \frac{P}{A}\ , \tag{2}$$

where P is the power entering a detector (i.e., pupil of eye, aperture of camera, etc.) and A is the area of the detector.

A point source radiates its power uniformly in all directions. Thus, if the intensity is examined at some distance, r, away from the source, then all of the energy must pass through the surface of an imaginary sphere of radius, r, with a surface area of $4\pi r^2$ (See Fig. 2). The intensity, I, at distance, r, is then,

$$I = \frac{P_S}{4\pi r^2}\ . \tag{3}$$

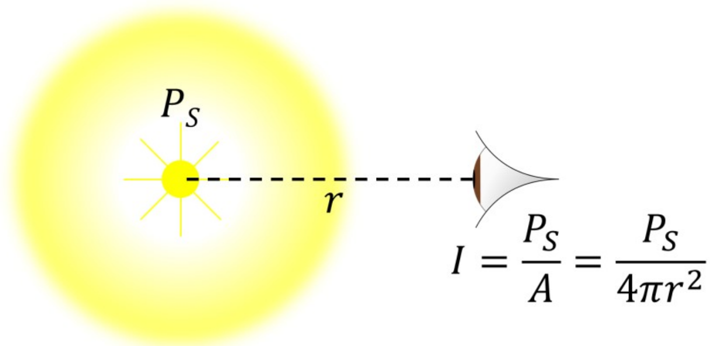

Fig. 2: Intensity from a point source decreases as the inverse square of the distance.

In other words, the intensity of light from a point source follows an inverse-square relation.

$$I \propto \frac{1}{r^2} \tag{4}$$

If we compare the relative intensities at two different locations, the ratio is found to be

$$\frac{I_2}{I_1} = \left(\frac{r_1}{r_2}\right)^2 . \tag{5}$$

Hence, doubling the distance from the source reduces the intensity by a factor of 1/4. Similarly, tripling the distance should decrease the intensity by a factor of 1/9.

Procedure:

Two identical, white LEDs will be used in this experiment. One is the point source of light and the second acts as a photocell detector. The source LED requires voltage to light up, so it will be placed in the breadboard for convenient wiring to a resistor and battery.

The detector LED will be held in a makeshift, clay holder aimed at the source, and its voltage output (proportional to light intensity) will be measured by a multimeter.

Build the Source LED Circuit

1. Prepare the source LED by constructing the circuit as shown in Fig. 3.
2. Note that LEDs allow current to flow in only one direction (like a turnstile at a sporting event). The source LED must be oriented as shown with the positive lead (long lead) in the more positive position (connected to the resistor) and the negative lead (short lead) in the more negative position (connected to the negative source wire). See Fig. 3a & b.
3. When placing the potentiometer in the circuit, make sure that each of the three pins are in separate rows. In this diagram (Fig. 3b), the breadboard is turned on its side with the rows (5 holes) running vertical.
4. The potentiometer (adjustable resistor) is used to adjust the voltage supplied to the LED. By turning the knob, you can turn on the LED and then increase or decrease the brightness (this circuit was demonstrated in Lab 0).
5. Locate the 470 Ω resistor from your lab kit.

   You can tell the resistor's nominal value from the 4 or 5-band color code printed on the resistor. To interpret this code, look up a resistor color code table or use an online calculator such as this one: https://resistorcolorcodecalc.com/.

6. The 470 Ω resistor is included to prevent too much current from flowing through the LED and burning it out.
7. Test the LED in the circuit to make sure it is a white LED and not a colored LED. All the LEDs are transparent so it will be impossible to distinguish them without testing.
8. Once the circuit is built and you know that the LED lights up, unplug the battery until you are ready to use it.
9. Notice in Fig. 3c that it may be useful to tape the battery to the back of the breadboard. This keeps it from unplugging accidentally and it helps the breadboard stand up easier.
10. If, when you start the experiment, you notice that the source LED is too dim (even with the potentiometer turned all the way up), check the battery voltage as you've done in previous experiments. If it is too low, it may not be able to supply enough voltage to light up the LED sufficiently. If that is the case, try a newer battery.

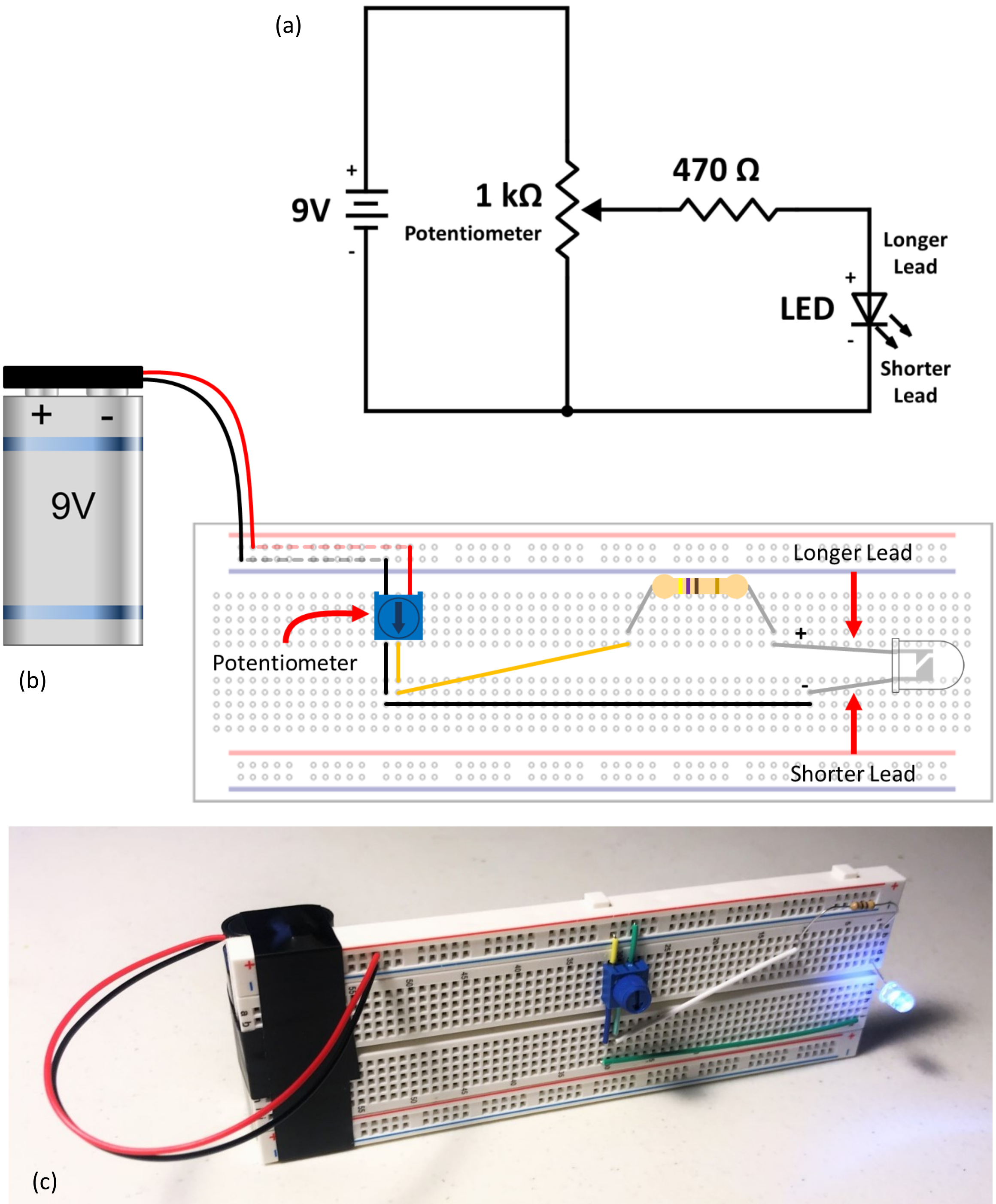

Fig. 3: Adjustable LED Circuit – (a) Circuit diagram for source LED,
(b) Breadboard wiring diagram, (c) Example circuit with battery taped to the breadboard

Build the LED Light Detector

WAIT: Before constructing the clay pillar, test the second LED (detector LED) in the breadboard circuit to verify that it is a white LED and not a colored one. All of the LEDs in your lab kit are transparent, making it impossible to distinguish them without testing.

1. Form a small pillar from your modeling clay as shown (see Fig. 4a).
2. Use a pen or similar tool to poke a hole through the pillar near the top (see Fig. 4b & c). The hole should be at about the same height as the source LED when the breadboard is lying on its side (look ahead at Fig. 8 to see why).
3. Set the LED just inside the hole such that the front of the LED is recessed from the opening (see Fig. 4d & f). Recessing the LED will somewhat shield it from ambient light.
4. Bend the LED leads apart, one to either side (see Fig. 4e). This will allow you to connect an alligator clip to each lead without them touching each other.
5. Press the clay in around the LED to hold it securely (see Fig. 4f).
6. Make sure the LED has a clear view straight out the front of the hole with no clay blocking its view (see Fig. 4f). If the LED is tilted at all, adjust its angle so it is pointing straight out the hole. If it is angled, it will not be as sensitive to the incoming light.
7. Adjust the height of the detector LED/pillar and/or the height of the source LED on the breadboard so that the two LEDs are at about the same height (look ahead at Fig. 8).

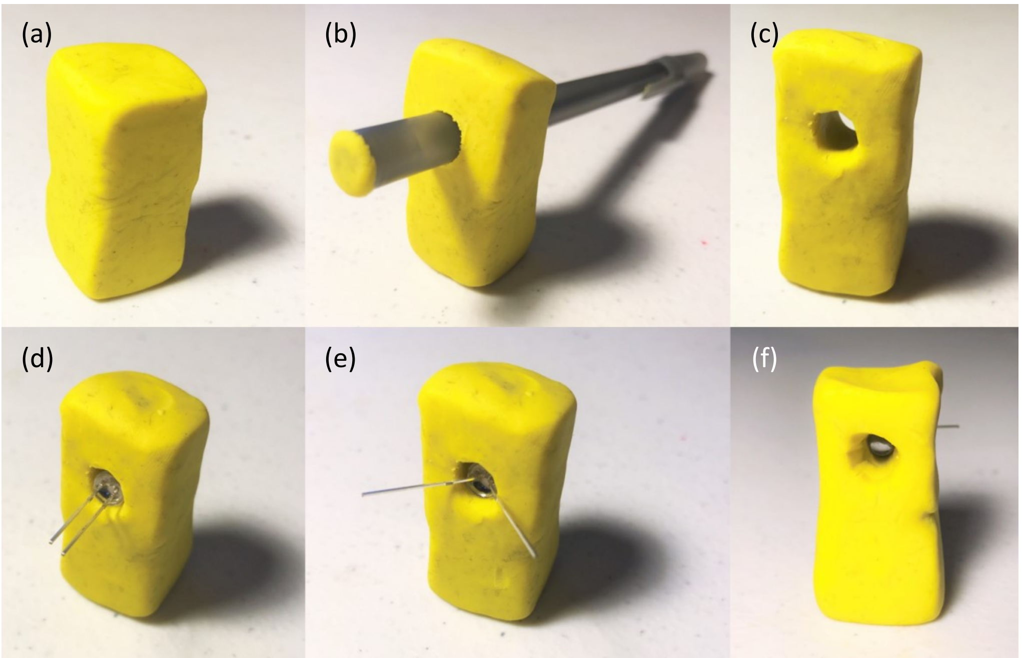

Fig. 4: (a) Clay pillar, (b) Make a hole in the clay. (c) Clay pillar with hole, (d) LED sitting loosely in hole with end of LED slightly recessed from opening, (e) LED leads bent out to the sides, (f) Clay squished in to surround LED on sides and hold it in place. LED must have a clean, clear view straight out the front of the clay holder (adjust if necessary).

8. Turn the multimeter dial to measure DC voltage (V ⎓), set it to the lowest voltage range (200 mV), and insert the probes in the appropriate ports (black in COM, red in V).
9. Use alligator wires to connect the red multimeter probe to the positive (long) lead of the detector LED and the black multimeter probe to the negative (short) lead of the detector LED (see Fig. 5).

   Note: If you happen to connect the leads backwards, the multimeter will register a negative voltage instead of positive. In case this, you can either switch the leads or treat the voltage as positive.

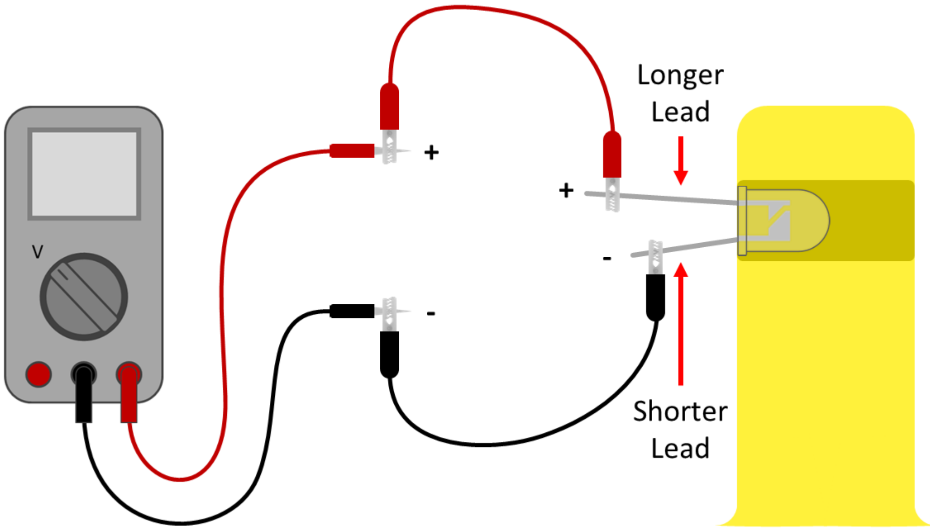

Fig. 5: Voltmeter connected to detector LED via alligator clip wires

10. Tape the ruler down to the table (without covering the centimeter markings). This will measure the distance to the light source.
11. Align the front end of the detector LED with the 0 cm mark on the ruler and face it toward the 30 cm end (see Fig. 6).

    Note: Since the detector LED is recessed from the opening, you will have to approximate where the front of the LED is and line up that point with the zero mark on the ruler. It might make it easier if you scratch a mark on the side of the clay where you estimate the front of the LED is.
    Then use this for alignment (see Fig. 8).

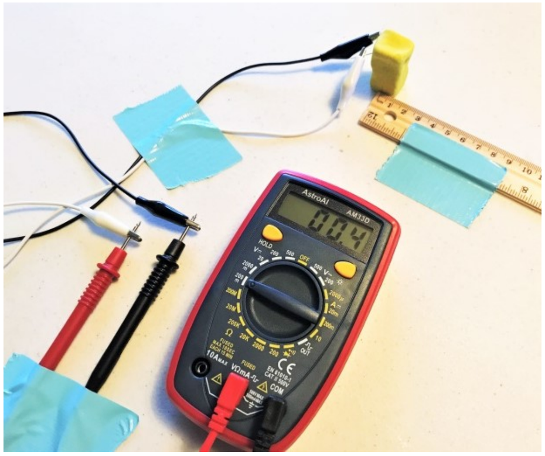

Fig. 6: Voltmeter connected to the LED. LED is aligned at 0 cm mark on the ruler. Everything is taped down to avoid unwanted shifting during the experiment.

Measure Light Intensity and Distance

Light intensity will be measured using the voltmeter. When light intensity, I, shines on the LED light sensor, the voltmeter (with its internal resistor) forms a complete circuit for current to flow, and this is detected as a voltage. In this situation, light intensity and electric current are directly proportional due to the way photons interact with electrons inside the LED, and since current and voltage are directly proportional (Ohm's Law), the measured voltage can be treated as a measure of light intensity.

1. Turn off all room lights, close the blinds, and check the voltage reading from the LED detector. Ideally, it should be zero if no light is shining on it. If it is not zero, make sure no other light sources are shining on it and check again. If it is not possible to eliminate all ambient light, record this baseline value and subtract it from all future voltage measurements.
2. Connect the battery, twist the potentiometer knob to turn on the LED light source, and point it directly at the detector LED. Then use a protractor or some kind of straight edge to align the front of the LED at the 30 cm mark of the ruler (see Fig. 7).
3. Once aligned at the 30 cm mark, remove the straight edge. Then tilt the source LED and/or breadboard slightly so that the brightest part of the light shines on the detector. Adjust the knob (increase the LED brightness) until the voltmeter registers a max voltage of about 1 mV (0.001 V). Make sure this voltage corresponds to the light shining directly at the detector and not at an angle or to the side of it.

   For the rest of the experiment, do NOT adjust the potentiometer. The brightness must stay the same throughout the experiment.

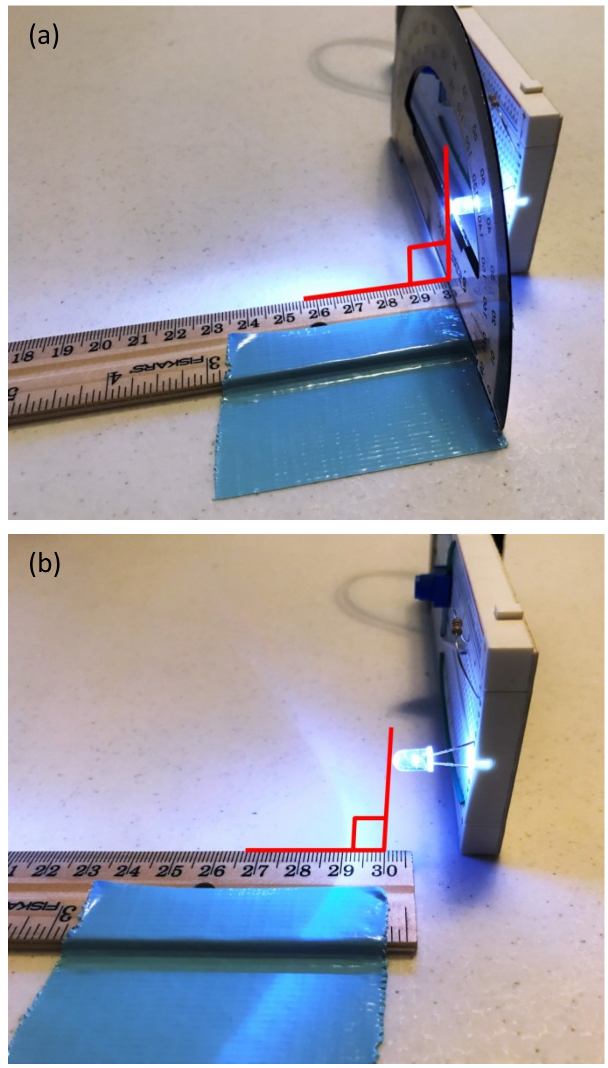

Fig. 7: (a) Protractor (or other straight edge) is used to align the source LED at the 30 mark. (b) LED aligned at 30 cm and shining at the detector LED.

Note: When the voltmeter is in the 200 mV range, the voltage displayed on the screen is most likely expressed in units of mV, not V. In that case, at 30 cm you want the max voltage to read "1" and not "0.001".

4. For the 30 cm position, record the voltage and distance in your eJournal.
   Record the data in whichever units are most convenient (mV/V and cm/m).
5. Move the source LED 2 cm closer to the detector (new position 28 cm) and line it up with the straight edge. Adjust the tilt of the source LED/breadboard until you find the angle that gives the maximum voltage reading. Record this voltage and the distance (28 cm).
6. Continue measuring the voltage and distance at 2 cm intervals (30 cm, 28 cm, 26 cm, 24 cm, …) until you get to 10 cm. Each time, slightly adjust the tilt of the source LED to find the maximum voltage reading for that distance.
7. Continue for distances from 10 cm – 1 cm at 1 cm intervals (10 cm, 9 cm, 8 cm, 7 cm …) until you cannot get any closer. You may have to stop before you reach 1 cm.
8. Closer to the detector, you will find the voltage to be very sensitive to the tilt of the light source, so take extra care to find the angle that produces the maximum voltage. As you tilt the LED/breadboard, make sure to keep the LED over the correct mark on the ruler.
9. Depending on how bright you originally set the potentiometer and how sensitive the LED is, you may need to switch the mode dial to the next higher voltage range for the last few measurements near the detector.

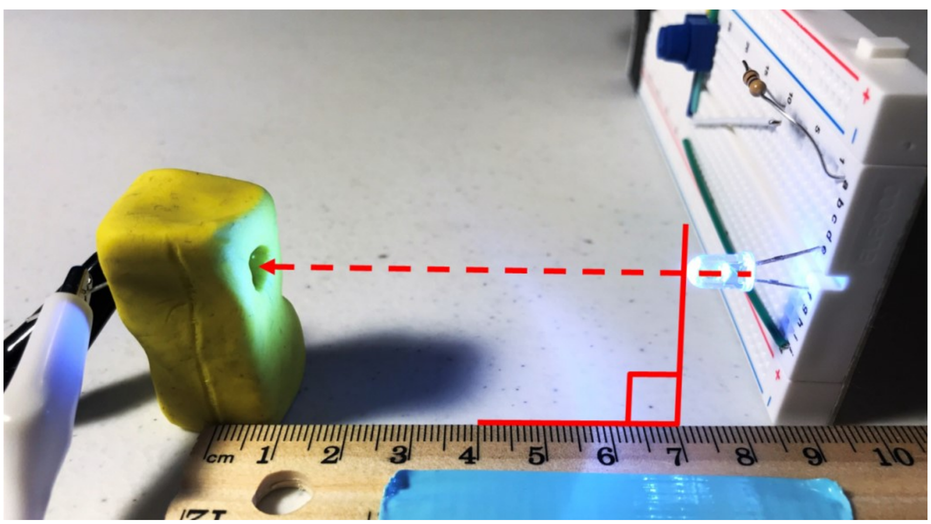

Fig. 8: Source LED aligned at 7 cm and shining directly at the detector LED

IMPORTANT: When you finish the experiment, turn off the multimeter to save the battery. The simpler inexpensive multimeters often do not shut off automatically.

Also, be sure to disconnect the battery from the source LED circuit. Even if you turned off the LED using the potentiometer, the potentiometer is still consuming power from the battery.

Analysis:

1. Copy the distance and voltage measurements into Graphical Analysis.
   Plotting the data in Graphical Analysis, rather than in Google Sheets or Excel, will make it easier later when excluding points from the curve fit.
2. Plot voltage (y-axis) vs. distance (x-axis) and apply a power law curve fit of the form,

   $$y = ax^b \quad . \tag{6}$$

3. When the light is bright enough (very short distances), the voltage may deviate from the power law trend. To correct for this, adjust the left edge of the curve fit to exclude those couple points (corresponding to distances of 1 cm, 2 cm, …). Look at your data to see which points deviate most from the trend and exclude those. Hopefully you won't need to exclude any more than 3-4 points.
4. Record the value of the fit parameter, b. For an inverse-square law, Eq. (4), one can expect the value of b to be -2. Compare b with -2 by computing the percent error.

   $$\%Error = \frac{|(-2) - b|}{|-2|} \times 100\%$$

5. Compute the ratio of the intensities (voltages) at 10 cm and 5 cm and compare to the prediction of Eq. (5), i.e., does doubling the distance lead to ¼ the intensity of light?
   If you previously had to exclude the 5 cm data point, just use two other points
   (ex. 6 and 12 cm or 7 and 14 cm).

   $$\frac{V_{10\ cm}}{V_{5\ cm}} = ?$$

6. If you compare two voltages farther out (ex. 20 cm and 10 cm), do you get about the same ratio as before?
7. Taking the log of Eq. (3) leads to

   $$log(I) = -2\, log(r) + constant \quad . \tag{7}$$

8. Use a spreadsheet or calculator to compute the values of log(V) and log(r).
   Use whichever log function is most convenient ($\log_{10}$(), ln(), etc.).
9. Construct a plot of log(V) (y-axis) vs. log(r) (x-axis) and perform a linear fit.
   Again, you may need to exclude some points on the left near zero because the voltage may deviate from the trend.
10. Record the slope, m, and compare it with -2 by computing the percent error.

    $$\%Error = \frac{|(-2) - m|}{|-2|} \times 100\%$$